EP 41890 (3)

3/5

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 November 2003 (20.11.2003)

PCT

(10) International Publication Number
WO 03/096757 A1

(51) International Patent Classification[7]: H05B 33/22

(21) International Application Number: PCT/US03/14600

(22) International Filing Date: 8 May 2003 (08.05.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/379,141 8 May 2002 (08.05.2002) US

(71) Applicant: ZEOLUX CORPORATION [US/US]; 704 228th Street, Sammamish, WA 98704 (US).

(72) Inventors: MAGNO, John, N.; 7 Renier Court, Middletown, NJ 07748 (US). KOCH, Gene, C.; 85 Cedar Run Road, Bayville, NJ 08721 (US).

(74) Agents: PARK, Eunhee et al.; Baker & McKenzie, 805 Third Avenue, New York, NY 10022 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

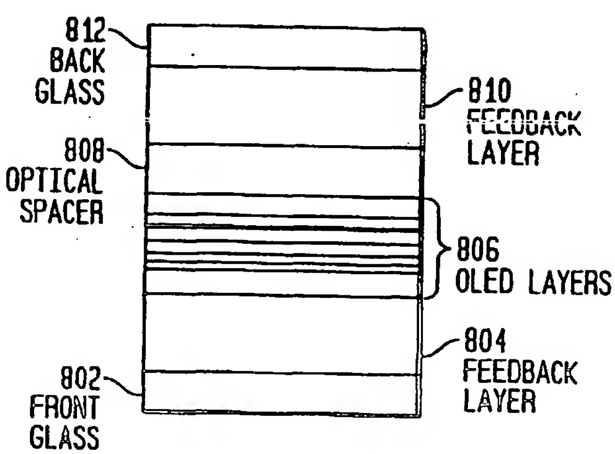
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

FP04-0321-00EP-NM
'07. 8.-1
SEARCH REPORT

(54) Title: FEEDBACK ENHANCED LIGTH EMITTING DEVICE



(57) Abstract: A feedback-enhanced light emitting device is disclosed. Feedback elements (804, 810) coupled to an emissive element (806) allows the emissive element to emit collimated light by stimulated emission. Feedback elements that provide this function may include but are not limited to holographic reflectors with refractive index that varies at least in part periodically and continuously.

WO 03/096757 A1

FEEDBACK ENHANCED LIGHT EMITTING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/379,141 filed May 8, 2002, incorporated herein in its entirety by reference thereto. This application is related to U.S. Patent Application Serial No. ____, filed on May 8, 2003, and entitled "LIGHTING DEVICES USING FEEDBACK ENHANCED LIGHT EMITTING DIODE," and U.S. Patent Application Serial No. ____, filed on May 8, 2003, and entitled "DISPLAY DEVICES USING FEEDBACK ENHANCED LIGHTING DIODE," which applications are incorporated herein in their entirety by reference.

TECHNICAL FIELD

The present application relates to light source devices, and particularly, to feedback enhanced light emitting devices.

BACKGROUND

Light emissive devices in the UV, visible and infrared spectral regions have a vast number of applications but present an even larger number of technical and economic challenges. One challenge is in efficiently producing the desired output light because the efficiency of producing output light may be reduced in any number of ways. For example, light may be internally reflected at refractive index boundaries; an excited energy state may be converted into heat rather than light; an excited energy state may be converted into light at a wavelength other than a desired

wavelength or wavelengths, for example, infrared, ultraviolet; light may be absorbed by component layers of the device including the light emitting material itself; and/or the emissive materials may have poor charge carrier injection efficiency. Because of these and other inefficiencies, the radiance level produced by a presently known emissive device may be insufficient for a particular application unless the emissive device is overdriven to achieve the desired radiance. Overdriving a light emissive device, however, may further reduce its efficiency and useful lifespan by increasing the amount of heat generated.

Further, light emissive devices made with organic light emitting diode (OLED) materials present difficulties in fabrication. Typical OLED light emissive materials include polymers or small molecules. Polymer OLED materials, however, are difficult to produce because of solubility or chemical compatibility problems. Further, although small molecules have sufficient vapor pressure such that the molecules may be deposited onto substrates by vapor deposition, small molecule OLEDs present different problems in that they are mechanically and thermally fragile.

It is possible to overcome these disadvantages by cross-linking these polymer OLED and small molecule OLED materials to produce a cross-linked OLED material. Cross-linking OLED phosphors, however, may reduce the conversion efficiency of excitons to photons to the point where a useful light emissive device does not result.

Similarly, light emissive devices made with inorganic light emitting diode (LED) materials have low efficiency in the conversion of energy to light. The low efficiency results from several factors including high absorption in the inorganic light emitting material and difficulty in coupling light out of the inorganic

light emissive material due to the high refractive index of the light emissive material. The overall efficiency can be increased when light emissive devices also include other elements such as a multi-layer dielectric distributed Bragg reflector (DBR), which are expensive to manufacture. The overall efficiency increase, however, is limited by the light losses in the DBR. Although the losses in the DBR can be improved through the inclusion of index matching layers, the index matching layers increase the cost and the number of layers in the device, further complicating manufacturing of these devices.

Furthermore, although additional elements may be included in emissive devices to improve a given characteristic of the devices, the improvement of a given characteristic is often a tradeoff with another characteristic and also complicates the emissive device by requiring additional processing steps to form the additional elements. For example, a multi-layer dielectric distributed Bragg reflector (DBR) may be used to increase the amount of stimulated emissions in the emissive layer at the cost of a substantial amount of light being lost. Index matching layers may also be included to reduce the amount of additional light loss. Such a method, however, greatly increases the number of layers in the DBR. Such devices also can be expensive and slow to produce, while only providing marginal improvements to its characteristics.

In the case of a multi-color emissive device, the challenge of producing efficient light emitting devices becomes greater. This is because the structure of the device often includes a greater number of more complex structures to handle multiple colors. The additional complexity adds further processing steps, which increase the cost and complexity of the manufacturing process while reducing the yield and output. The added

structures require more precise positioning and are more difficult to fabricate with optically smooth surfaces. Additionally, color emissive devices often have poor color rendition because the use of broadband emissive material. Accordingly, a need exists for a more efficient light emitting device.

SUMMARY

A feedback enhanced light emitting device is disclosed. The device in one aspect comprises an emissive layer disposed between two feedback layers. The emissive layer is adapted to emit light wherein the two feedback layers reflect at least some of the light back to the emissive layer, thus stimulating emission. In one aspect, at least one of the two feedback layers has at least in part periodically and continuously varying refractive index profile along an axis normal or substantially normal to a plane of a respective layer.

In another aspect, the feedback layers may comprise a hologram formed from a photopolymer having an optically written sinusoidally varying refractive index profile. In another aspect, the emissive layer may comprise cross-linked polymer.

In another aspect, a method of fabricating the feedback layers comprises disposing a layer of polymer on a substrate and exposing the polymer to light to record one or more interference patterns on the polymer. In one aspect, the polymer is exposed to light to cause cross-linking.

Further features as well as the structure and operation of various embodiments are described in detail below with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates an emissive device in one embodiment.

Fig. 2 illustrates the critical angles at which light undergoes total internal reflection.

Fig. 3 is a graph showing the efficiency, brightness, and voltage of an OLED device.

Fig. 4 illustrates a device including a resonant cavity equivalent.

Fig. 5 illustrates a pixelated device with a broadband emissive layer and two pixelated feedback layers.

Fig. 6 illustrates a one-dimensional photonic refractive index profile of a cholesteric liquid crystal.

Fig. 7 illustrates a feedback enhanced light emitting device in another embodiment.

Fig. 8 illustrates a feedback enhanced light emitting device having an OLED emissive element, two holographic feedback elements and an optical spacer in another embodiment.

Fig. 9 illustrates a feedback-enhanced OLED structure in one embodiment.

Fig. 10 illustrates an example of a double mask apparatus for producing a patterned hologram in one embodiment.

Fig. 11 illustrates an example of a single mask apparatus in for producing a patterned hologram in one embodiment.

Fig. 12 is a graph illustrating irradiance versus position in the double mask apparatus of Fig. 10.

Fig. 13 is a graph illustrating irradiance versus position in a single mask apparatus of Fig. 11.

Fig. 14 is a graph illustrating exposure rate

versus irradiance dose for a material used for hologram with irradiance threshold = a.

Fig. 15 is a diagram that contrasts a structure of a single-mode FE-OLED and a multi-mode FE-OLED.

DETAILED DESCRIPTION

Fig. 1 illustrates an emissive device in one embodiment. The device 1 includes an emissive layer 2 and a feedback element 4. The feedback element 4 may be a layer with a periodically and continuously varying index of refraction that allows some light to be transmitted through the feedback element 4. A second feedback element 6 may also be included such that the emissive layer is between the two feedback elements 4, 6. The second feedback element 6 may allow some light to be transmitted through the second feedback element 6 or substantially reflect the light incident upon it. In one embodiment, a structure with a periodic index of refraction variation, a plane mirror, a distributed Bragg reflector (DBR), or another reflector may be used as the second feedback element 6.

In one embodiment, the device shown in Figure 1 allows light emanating from the emissive layer in a direction that is normal to the planes of the two feedback structures to substantially reflect back and forth between the two feedback structures. In passing through the emissive layer multiple times, the emission of additional light is stimulated by interacting with the excitons in the emitter. Excitons are excited state pairs of electrons and holes whose collapse leads to light emission in luminescent materials. In this way the amount of light propagating normal to the plane of the device is increased at the expense of light propagating in the plane or at oblique angles. Since the in-plane and obliquely propagating light does not normally escape

the luminescent device, this enhancement of normal to the plane emission considerably increases device efficiency.

In one embodiment, if the feeding back of emitted light and subsequent stimulated emission are very efficient, all light will be emitted along the vertical axis and will be substantially coherent. In this case, the device becomes a vertically emitting laser or VCSEL (vertical cavity surface emitting laser). However, laser action need not occur in order for the emitted light to be substantially collimated and thus for the device to have considerably enhanced energy efficiency. Because in these devices the efficiency enhancement is due to feedback light, the devices are referred to as feedback enhanced luminescent devices or feedback enhanced light emitting devices.

The device in one aspect may also include other elements such as an anode, a cathode, carrier injection and transport layers, a transparent buffer layer lying between the feedback layers and the emissive layer, or other elements. Fig. 7 illustrates an emissive device 700 having additional elements. An integrated light diffuser may also be added outside of the feedback layers.

In one embodiment, one or more methods for supplying excitation energy to the emitter generally may include electrical excitation or photo-excitation. If the excitation is electrical current, it may be introduced into the emissive layer through a pair of electrodes to induce electroluminescence. For example, a pair of electrodes such as a cathode 102 and an anode 104 may be placed between an emissive layer 2 and the feedback layers 4 and 6, respectively.

The cathode 102 may include a transparent conductive structure with a low work function surface adjacent to the emissive layer 2 such that it is able to

inject electrons into the emissive layer 2. In one aspect, for the cathode 102 to have the desired transparency, a two-layer cathode may be provided. The two-layer cathode may include a very thin, for example, 5 nanometer (nm.) metal cathode such that the metal is transparent or nearly transparent. The metal may then be backed, for example, on the feedback layer side, with a transparent conductor like indium-tin oxide (ITO) to yield high enough conductivity to have a low impedance device. The anode 104 may include a transparent conductive material chosen to have a high work function such that it is able to inject holes into the emissive layer 2.

The emissive layer 2 may include an electroluminescent material whose spectral emission band overlaps the reflection bands of the feedback layers 4 and 6. In one embodiment, the emissive material is an organic luminescent material and the device is referred to as a feedback enhanced organic light emitting diode (FE-OLED). Alternatively, the emissive material may be an organometallic luminescent material, a luminescent inorganic semiconductor material such as GaAs, AlGaAs, or InGaN, or an organic/inorganic composite luminescent material. In another aspect, the emissive layer 2 may be a fluorescent or phosphorescent emissive material.

The feedback layers 4 and 6 may include light non-absorbing material with a periodically varying index of refraction. A way of describing the function of these structures is that the light entering the feedback layer material along the layer normal axis suffers a small reflection each time it passes through one cycle of the refractive index oscillation. When the feedback element is thick enough, the feedback element may act as a nearly perfect reflector at the resonant wavelength, 2d, where d is the pitch of the refractive index spatial oscillation.

The feedback layers in one aspect may be fabricated from plane wave holograms with peak reflectivity at the desired emission wavelength.

In one embodiment, the device 700 shown in Fig. 7 may be inverted. That is, the position of the cathode 102 and the anode 104 may be interchanged.

The device 700 also may include a substrate 106 placed adjacent to a feedback layer, for example the feedback layer 6. The substrate 106 is used as a layer on which the device 700 may be built. In one aspect the substrate 106 may be comprised of a transparent material. In one aspect, a material may be applied over the device 700 to function as a cover 108. The cover 108, for example, functions to hermetically seal out ambient water and oxygen, or otherwise to protect the device 700 from chemical or other degradation.

Other components of the device 700 may include a hole transport layer between the anode 104 and the emissive layer 2. The hole transport layer may be used to allow more electron/hole recombination to occur at the emissive layer 2. For example, in emissive layers having imbalance between electron and hole mobilities, usually with low hole mobilities, the electron/hole recombination tends to occur at the anode. Similarly, a device with a direct anode/emitter interface tends to be inefficient because many traps, that is, sites at which non-radiative de-excitation of the emitter occurs, exist at the emitter/anode interface. Using hole transport layers, for example, with high hole mobilities minimizes the problem of the electron/hole recombination occurring at the anode. The hole transport layer may also be chosen to have a hole conduction band intermediate between those of the anode 104 and the emissive layer 2, thus providing more efficient hole injection from the anode into the emitter.

A hole injection layer may also be provided between

the anode 104 and the hole transport layer. For example, if anode materials like indium-tin oxide (ITO) having less than well defined band structures that may lead to inefficient hole injection into the device are used, hole injection layers like copper phthalocyanine may be provided to better define band structure with energy level intermediate between ITO and hole transport materials. Providing the additional hole injection layers thus may assist hole injection and produce a more efficient device. Hole injection layers, however, are not required.

In another embodiment, additional hole transport layers may be inserted between the hole injection layer and the emitter to further smooth out band energy differences. If the hole transport layer adjacent to the emitter has its electron conduction band at an energy level nearly the same as the emitter, electrons may "overshoot" the emitter with recombination occurring in the transport layer rather than the emitter. This overshoot may be eliminated by interposing an electron blocking layer that has a high energy electron conduction band, but good hole conduction, between the emitter and the transport layer.

In another embodiment, an electron transport layer may be provided between the cathode 102 and the emissive layer 2. The electron transport layer performs the similar function for electrons that the hole transport layer performs for holes. As with hole transport layers, additional electron transport layers may be added to assist band energy matching.

In another embodiment, an electron injection layer may be provided between the cathode 102 and the electron transport layer. In one embodiment, a low work function material may be used for the cathode 102. With a low work function material less energy is expended injecting electrons into the device. For example, very low work

function metals such as calcium may be used, although calcium may be chemically reactive and sensitive to moisture and oxygen. Aluminum also may be used. For instance, overcoating the aluminum with a very thin film of materials like lithium or magnesium fluoride provides a "band bending" effect that helps relieve the band energy mismatch.

In another embodiment, a hole blocking layer may be provided between the emitter and hole transport layer to reduce hole "overshoot" from the emitter. The above described carrier transport, injection, and blocking layers are also typically used in the conventional OLED devices. Accordingly, further details of these elements will not be described herein.

In one embodiment, the device 700 may also include a buffer layer, for example, a clear dielectric interposed between an electrode and a feedback layer. When the buffer layer is placed between the cathode 102 and the feedback layer 4, it may act as a hermetic barrier between the cathode and the outside environment especially during subsequent processing. In one embodiment, the buffer layer also provides the right size spacing such that destructive interference of light in the gap between the two feedback layers does not occur. To achieve this function, the buffer layer may be inserted between the feedback layer and the electrode to adjust the optical thickness of the device. The buffer layer may also be used to maintain the proper phase relationship between the refractive index profiles in the two feedback layers. In addition the buffer layer may be used to adjust the thickness of the gap between the feedback layers thereby tuning the wavelengths of the modes of the light that is resonating in the gap.

An example of a buffer layer arranged on a device in one embodiment is shown in Fig. 8. Fig. 8

illustrates a device that includes an emissive element 806, for example, an OLED layer, two feedback elements 804 and 810, for example holographic layers, and a buffer layer 808, for example, an optical spacer. As shown in Fig. 8, the emissive element 806 may include a plurality of layers. The device also may include a front glass 802 and a back glass 812.

The devices shown in Figs. 1, 7, and 8 may substantially reduce or eliminate the light losses, for example, due to total internal reflections that may otherwise occur at the refractive index mismatch at boundaries. This approximately doubles the amount of light extracted from the device through, for example, a substantial elimination of light absorption loss inside of the device.

In one aspect, referring back to Fig. 1, the feedback elements 4, 6 located on either side of the emissive layer 2 form a resonant cavity. The feedback elements 4, 6 reflect light back into the material of the emissive layer 2 and allow stimulated emission to occur when sufficient light is reflected into the emissive layer 2. For example, the number of interactions between photons and excitons regulate the rate of stimulated emission. Thus, for example, by localizing light in the resonant cavity and thus causing a high density of photons at the emissive layer 2, a very rapid stimulated emission conversion may be produced.

Typically, without the induced stimulated emission, spontaneous emission, which is a relatively slow and purely statistical process, dominates the light generation process in an emissive material. In one embodiment of the present disclosure, the rapid conversion to stimulated emission leaves the spontaneous emission process with little or no excited state energy to convert to light. An even slower process, non-

radiative de-excitation, converts excited state energy to heat. Thus, stimulated emission in one embodiment preempts conversion of excited state energy to heat since the mechanism of heat formation is orders of magnitude slower than that of stimulated emission. Thus in one embodiment, the excited state energy of the device 1 may be converted predominantly into light, not heat. The consequent reduction in heat generation in this embodiment also may result in reduced temperature in the device, which may allow for a longer life and more efficiency in the device.

In conventional light emitting devices, the light absorption loss occurs because light is emitted at oblique angles to the plane of a device and reflected. For example, Fig. 2 illustrates the critical angles at which light undergoes total internal reflection. Light strikes the refractive index boundaries between a high refractive index layer 8 and two adjacent layers 10 and 12, at angles exceeding the critical angle at which light undergoes total internal reflection. The reflected light is effectively trapped within the high index layer 8 and does not contribute to the radiance level of a device. In one embodiment of the method and apparatus of the present disclosure, by allowing the light to emit normal to the plane of a device and thus reducing the internal reflection, higher radiance level may be achieved with lower driving voltages. Lower driving voltages in turn may contribute to extended lifetime of a device.

Fig. 3 is a graph illustrating the efficiency, brightness, and voltage of an OLED device. Driving an OLED device at lower voltages while achieving the desired radiance level has a great impact on the efficiency and longevity of the device. This is due to OLED material having peak efficiency soon after light generation begins as drive voltage is increased and

rapidly declines thereafter with increasing voltage. Thus, achieving the desired radiance levels at lower driving voltages through stimulated emission has a great impact on the power conversion efficiency and longevity of OLED devices.

In one embodiment, with the sufficient levels of light feedback and resulting stimulated emission, the device 1 may be used as a laser. Further, even if stimulated emission in the light emissive layer 2 does not lead to lasing, the device 1 may exhibit improved luminous efficiency. The improved luminous efficiency occurs, for example, because in one embodiment the total amount of light exiting the device 1 is substantially increased by the increased production of light being emitted normal to the plane of the device 1 as compared to light being emitted at angles that result in total internal reflection. In one embodiment, the emissive layer 2 may comprise cross-linked organic light emitting diode (OLED) materials such as a small molecule or polymer OLED or molecules of molecular weight intermediate between the two. Although in known devices, cross-linking normally causes the excited state energy to convert into heat, the feeding back of emitted light into the emissive layer, in one embodiment of the present disclosure, and the subsequent rapid stimulation of light emission from the emissive layer that may occur, changes the dominant mode of de-excitation in cross-linked emitter materials from heat to the stimulated emission of light. Thus, in one embodiment, the one or more feedback layers of the present disclosure allows the OLED devices to include conventional photo-induced and other cross-linked techniques. Accordingly, the solubility problems of polymer OLED materials and thermal fragility of small molecule OLED materials may be avoided.

In another embodiment, the emissive layer 2 may

include a small molecule emitter dissolved in a polymer host. Structures of this type may be fabricated by solvent casting, for example, spin coating a solution including a phosphor, a monomer, an initiator, and a solvent. The polymer host dissolving may increase the thermal and mechanical stability of the small molecule phosphor.

After the coating is dried to remove the solvent, the coating may be cross-linked by exposure to ultraviolet or other light resulting in a tenacious film that may be used as an emissive layer 2. In one embodiment, both cross-linking the phosphor and including a small molecule phosphor in solution in a polymer host facilitate light emitting layer patterning by patterned exposure. Both may also be used to fabricate highly efficient devices where stimulated emission enabled by the presence of feedback layers is the dominant de-excitation process.

In another embodiment, emissive layer 2 may comprise an aligned liquid crystal material (for instance, in the nematic phase) that has been rendered immobile by either cooling into a glass phase or cross-linking as described above. The emitter molecules may also be guests in a liquid crystalline host solvent. Devices with emitters that have liquid crystalline order may emit light with some level of plane polarization. They may be combined with the polarized feedback layers described below.

In one embodiment, a feedback element is selected such that it returns a desired percentage of emitted light back into the emissive layer 2 with very high efficiency. Selecting the appropriate feedback element may increase and maximize stimulated emission of light from the emissive layer, thereby increasing the total light output from the device. The light from the stimulated emission process propagates normal to the

plane of the device ensuring nearly complete coupling of light out of the device. As described above, having light emitted normal to the plane may reduce light loss due to total internal reflection. Further, the feedback element may be selected such that light absorption losses in the feedback element are reduced.

In one embodiment, the feedback layer may be designed to have a refractive index profile such that the light losses in the feedback layer may be reduced or avoided. The reduction in light absorption in the feedback layer may allow sufficient recirculation of light to cause stimulated emission to dominate the light generation process.

In one embodiment, for example, having continuous variation in the refractive index of the feedback layer in contrast to abrupt or discontinuous changes, for instance, as in DBR reflectors, may minimize the light losses in the feedback layer. In one embodiment, the continuous variation is periodic, that is regularly cyclically varying in value. For example, a feedback layer may have index variation meeting the Bragg condition: $2d\sin\theta = n\lambda$, where d is the period of the cyclical variation in refractive index in a volume grating, θ is the angle of incidence of light on the grating, where $\theta = 90°$ and $\sin\theta = 1$, n is an integer representing the order of the reflection, and λ is the wavelength of the light that is desired to be reflected.

In another embodiment, all of the refractive index variation need not be periodic with $2d = n\lambda$. Other purely random variation may be superimposed on top of the desired periodic variation. Yet in another embodiment, multiple periodic spatial frequencies of variation may be superimposed.

Useful refractive profiles include, but are not

limited to, sinusoids, continuously varying sinusoidal like functions, and the convolution of a sinusoid function offset so that sin(y) assumes no negative values or a Gaussian function with a comb function.

In another embodiment, feedback layer elements may include a refractive index profile designed to increase or maximize the coupling of light out of the emissive layer. For example, the refractive index profile may be one intermediate between a square wave profile (discrete layers) and a sinusoidal profile.

Sinusoids and refractive index profiles intermediate between sinusoids and square waves are producible holographically. A plane wave hologram may be an example of an element that has a continuously varying refractive index profile. For example, a hologram with a sinusoidally varying refractive index profile may be optically written into a feedback layer formed from a holographic film.

In one embodiment, using holographic feedback layers may allow the refractive profile of the feedback layer to be tuned from a nearly sinusoidal to a nearly square wave profile by tuning the contrast function of the holographic film. The result may be the ability to tune the spectral width and shape of the feedback layer reflection band.

The refractive index profile in a feedback layer is not limited to reflecting a single wavelength, but may include in one embodiment a superposition of two, three, or more profiles at different pitches such that the reflection of multiple wavelength bands may be performed by the same feedback layer. Alternatively, the profile may have discontinuities or a region of constant refractive index between regions of continuous variation, or may include a plurality of the individual feedback layers as described above.

In another embodiment, the refractive index profile

of the feedback element may be such that the amount of light produced by stimulated emission is increased compared to light produced by spontaneous emission or other processes, while simultaneously light absorption losses in the feedback layer are reduced or avoided, both factors contributing to increase in the light coupled out of the device.

For example, the feedback layer may be designed to have a proper ratio of light exiting the device to light reflected back into the emissive region. This ratio is a function of the small signal laser gain of an OLED structure. Thus, the ratio may vary with both the emitter and other materials used in an OLED and the exact structure of an OLED device. The proper ratio, for example, may be generally determined by balancing between production of additional light through stimulated emission and absorptive loss of light in an OLED structure. Small signal gain is the net amount of light gain per input photon flux extrapolated down zero photon flux. The reason for this extrapolation is that each pass of light through the device reduces the population of excitons due to stimulated emission. Thus the gain in light output decreases for each successive pass while the absorption losses remain constant. Since different emitters have different intrinsic small signal gains and since different emitters require different carrier layers, layer thicknesses, etc. that result in different levels of absorbance, each type device may have a different ratio. Having this proper ratio in one embodiment may increase the amount of light produced by stimulated emission as compared to light produced by spontaneous emission. For instance, if too high a ratio of light is reflected back into the emissive layer, more than an optimum amount of light absorption may occur in the device as photons make multiple passes through any light absorbing materials in a resonant cavity of the

device. On the other hand, if too high a ratio of light is allowed to escape the device, insufficient light may be reflected back into the emissive layer and inhibit maximizing of stimulated emission.

In one embodiment, this proper ratio of light fed back to light transmitted in the feedback layer may be achieved by properly adjusting the physical thickness of the layer or the delta n (maximum amplitude) of the refractive index variation in the layer. These parameters may be varied to select the desired feedback to transmission ratio. For example, a 7 micron thick layer of Slavich PFG-03C holographic emulsion used as a feedback layer provides a hologram with about 96% reflectance after optimum processing.

When this ratio is properly selected, an emissive layer that normally emits light over a wide range of angles in at least one dimension, if not isotropically in all directions, now may be enabled, for example, with sufficient gain in the stimulated emission process, to emit light in the form of stimulated emission along the axis normal to the feedback elements.

In one embodiment, feedback layers with at least in part periodically and continuously varying refractive index profiles may be at one side of the device or may be at both sides. Where only one feedback layer that is at least in part periodically and continuously varying is used, a second layer of reflective materials such as a mirror, a metallic surface, a layered dielectric distributed Bragg reflector (DBR), or reflective anodes or cathodes may be used as the feedback layer on the other side of the device. A distributed Bragg reflector is a reflector composed of a stack of layers of dielectric material of alternating refractive index. Such a stack has discontinuities in the value of the refractive index at the layer boundaries.

In another embodiment, feedback structures with

periodic and continuous variation in refractive index may act as photonic crystal structures. A photonic crystal is a material that because of a periodically varying refractive index along one or more axes cannot support light propagation of particular frequencies along those axes. In sufficient thickness it thus becomes a perfect reflector over some spectral reflection band along those axes and is said to have a photonic band gap of light energies it is incapable of supporting. One-dimensional photonic crystal structures that may be used for the feedback layers in one embodiment may comprise layers of material in which the electron density and therefore the refractive index has a uniform periodic and continuous or other appropriate variation along the axis normal to the plane of the layer. The variation need not be sinusoidal in nature, but may include a dominant periodicity in the structure of the material that is n/2 times the wavelength of the desired stimulated light emission where n is some integer, for example 1. Generally, n=1 is equivalent to the standard half-wave multilayer reflector. Alternatively, reflective layers with higher values of n may be made. Holography usually produces n=1 devices. For devices in which the layers are produced discretely one at a time, the layers may be produced with more thickness. To maintain constructive interference in one embodiment, n may be an integer. In another embodiment, two and three dimensional photonic crystal structures may be used as feedback layers.

Fig. 4 illustrates a device 20 with photonic crystal feedback elements that produce stimulated emission in one embodiment. The device may be created by placing the feedback elements or layers 22 on both sides of an emissive element or layer 24. If the device 24 is transparent to the desired wavelength of light, for example, light emitted normal to the plane of the

emissive element or layer 24 and the surrounding feedback elements or layers 22 may be reflected multiple times through the emissive element or layer 24. When the emissive element or layer 24 is an OLED, for example, the light may be reflected multiple times through the exciton rich region of the OLED. This may produce the stimulated emission of coherent light collimated normal to a plane of the device in one embodiment of the present disclosure.

A feedback enhanced luminescent device in one embodiment utilizes a photonic crystal behavior of dielectric materials with at least in part periodically and continuously varying indices of refraction to concentrate feedback light intensity in the exciton rich zone of the emitter material. For example, in one embodiment, this concentration of intensity may be enabled by using device configurations, band-edge feedback enhanced luminescent devices or defect-mode feedback enhanced luminescent devices, for instance, band-edge FE-OLEDs and defect-mode FE-OLEDs.

In a band-edge embodiment, the feedback elements that define both ends of the device resonant cavity may be completely reflective at at least one wavelength in or near the emission band of the emissive material. Both of the feedback elements in one embodiment are photonic crystal feedback layers, as previously described above, having the center wavelength of their reflective bands slightly offset from the maximum of the fluorescence band of the emissive layer. Stimulated emission occurs in this device at a band edge of the reflective band of the feedback layers. In one aspect, the band edge at which stimulated emission occurs is on the side of the reflection band nearest the emissive material's wavelength of maximum emission. Alternatively, stimulated emission at both edges of the feedback layer reflection band may occur with a broad

band emissive material.

In another aspect, a band-edge emitting device may be realized by having both reflectors that are completely reflective holographically written feedback layers with their wavelengths of maximum reflection, for example, identically offset in wavelength from the emission maximum of the OLED or LED emissive material.

In a band-edge device in one embodiment, a photonic band gap in the photonic crystal structure is created, thereby improving performance of the band-edge device. In photonic crystal materials, light with wavelengths in the spectral reflection band of the material is not only reflected by the periodically varying refractive index structure, it also cannot be propagated within the structure. That is to say, the wave propagation modes that light normally has in free state cannot exist in the photonic crystal. Thus, the material has a photonic band gap in photon energies analogous to the electronic bandgap in electron energies in some crystalline materials. Band-edge lasing is enabled, for example, because the wave propagation modes that are at forbidden wavelengths in the photonic crystal structure are not destroyed, but are expelled to the edges of the photonic band gap (in terms of wavelength), yielding a high density of modes at wavelengths at the reflection band edges. This is equivalent to saying that there is a high density of optical states at the band-edge wavelengths in the photonic crystal. A material embedded in the photonic crystal structure sees this high density of states at those wavelengths. The result is a very intensive interaction of light at the band-edge wavelengths with the embedded material and the potential for very intensive stimulation of light emission.

In another embodiment, the layer of luminescent material and surrounding device structures (e.g. an

OLED) may serve to offset the phase of the refractive index alternation in the photonic crystal layer on one side of the device from the phase of the refractive index alternation in the photonic crystal layer on the other side of the device. In this embodiment, the luminescent material, for example, the OLED layers act to create a defect in what would otherwise be a continuous, periodic variation in refractive index from top to bottom in the device. In one embodiment, the thickness of the OLED may be the equivalent of less than one wavelength of light at the central wavelength of the photonic crystal reflection band. In devices of this type, a defect-mode of light propagation is induced that is highly localized in the area of the OLED. This in turn results in extremely efficient interaction of feedback photons with excitons to produce stimulated emission. As in the case of the band-edge lasing feedback enhanced device, the defect-mode device may have very energy efficient light emission and low current threshold of lasing.

In another embodiment, the feedback enhanced luminescent devices may be single-mode or multi-mode devices. Single-mode devices may be produced by fabricating devices with resonant cavities (distances between feedback layers) with widths of approximately the wavelength of light emitted by the emitter while multi-mode devices have resonant cavities with widths at least several times larger than the wavelength of light emitted by the emitter. For example, Fig. 15 contrasts the structure of a single-mode FE-OLED 1502 and a multi-mode FE-OLED 1504. The single mode FE-OLED 1502 has the holographic feedback layers 1506, 1508 inside a glass package with a resonant cavity width of about 400 nm, a mode spacing of approximately 0.5 µm and a spectral linewidth of around 1.5 nm.

The multi-mode FE-OLED 1504 in one embodiment has

the holographic feedback layers 1510, 1512 outside the glass package. For example, a mode spacing of approximately 0.2 nm occurs with the feedback layers separated by 1 mm and using 500 nm wavelength light. Spectral line width is determined by the reflective bandwidth of the feedback layers 1510, 1512 and is around 100 nm. In the multi-mode device 1504, the holograms may be applied after the OLED is assembled.

In another embodiment, the multi-mode device may have the feedback layers inside the glass package or one feedback layer inside the glass package and one feedback layer outside the glass package. Transparent spacers including relatively thick transparent spacers may be used to fill space in between the emissive device and the feedback layers thereby establishing the desired resonant cavity thickness. In this approach, cavity thickness may be established independently of mechanical considerations in device packaging and may be used to provide a multi-mode device that may be pixelated without parallax issues.

To a first order of approximation, in one embodiment, a single-mode device with feedback layers has a resonant cavity thickness of one-half the wavelength of the desired output light and with the same phase of the periodic index variation at both feedback layers inside surfaces. Other thicknesses of the same order of magnitude and other phase relationships may be used.

To provide the desired light output from a feedback enhanced device, the light generated in one embodiment may be coupled out of the device in one or both directions normal to the plane of the device. This may be achieved by manufacturing or thinning one or both of the two feedback layers such that there is an insufficient number of cycles of refractive index variation to completely reflect the light produced and

thus allowing light to be emitted from that feedback layer.

Another approach to "thinning" one or both of the feedback layers is to maintain their thickness at some standard value (e.g., 7 microns) while reducing the delta n of the refractive index variation in the feedback layer. In the case of holographic feedback layers this may be done by reducing the total exposure used to write the hologram.

In alternative embodiments, to form the above-described photonic crystal feedback layers, the following materials may be used as feedback layers, but are not limited to only such: homogenously aligned monomeric and polymeric chiral liquid crystals, opals, or other particulate agglomerates that have structures akin to a crystal lattice; middle phase lyotropic liquid crystals either in a fluid or a polymerized solid phase; or block copolymers in phases with liquid crystalline structures in which the oligomeric blocks form repeat units of the requisite length to yield a structure with the desired periodic and continuous variation in refractive index.

A block copolymer may be a self-assembled organic photopolymer structure produced by consecutive linking of monomer or oligomer elements into a self-assembled polymer structure. A one-dimensional photonic crystal structure also may be created by vacuum depositing a dielectric material of continuously varying composition such that the resulting structure has the desired index profile or an approximation of the desired index profile.

In one aspect, the desired index profile may depend on the individual device. For instance, band-edge lasing devices may require broader spectral reflection bands than other devices. In this case a refractive index profile more closely approximating a square wave

profile may be used.

A more detailed description of the fabrication of plane wave holograms is provided in the following description. In one aspect, the feedback layer may contain a refractive index profile that is recorded into a medium. For example, the refractive index profile may be an interference pattern recorded into a photopolymer medium by optical interference or a similar interference pattern recorded into a photosensitive medium. The photosensitive medium may be a silver halide sensitized gelatin emulsion such as Slavich PFG-03C, which currently is available from UAB Geola, P.O. Box 343, Vilnius 2006, Lithuania. Details concerning fabrication of holograms from this material may be found in J.M. Kim, et al.; "Holographic optical elements recorded in silver halide sensitized gelatin emulsions. Part 2. Reflection holographic optical elements" Applied Optics 41, pp. 1522-33 (10 March 2002) and J.M. Kim, et al.; "Holographic optical elements recorded in silver halide sensitized gelatin emulsions. Part 1. Transmission holographic optical elements" Applied Optics 40, pp. 622-32(10 February 2001), which are incorporated herein by reference. A refractive index profile may be recorded into a medium with a reverse contrast photosensitivity, for example, by using positive or negative photosensitive materials. Holograms may also be made by the use of dichromated gelatin or other photosensitive materials.

Refractive index profiles may also be recorded by non-optical means such as a self-assembled organic photopolymer structure produced by consecutive linking of monomer or oligomer elements consecutively into a self-assembled polymer structure or a polymerized middle phase of a lyotropic liquid crystal. Refractive index profiles may also be written using an electron beam resist.

In another aspect, holograms may also be made from a film of photopolymer material. The photopolymer material may be formed from mixture of monomers such as an approximately 50:50 mixture of ethoxylated bishpenol A diacrylate and trimethylol propane triacrylate. These materials are available from Sartomer Corp., Exton, PA. Upon the addition of a suitable photoinitiator, a hologram may be recorded into the mixture.

In one aspect, a hologram may be produced at the desired wavelength or may be produced at the double or another integer multiple of the desired wavelength. This may be used in encoding multiple colors in the same device. Alternatively, recording methodologies may be combined.

In another aspect, a hologram feedback layer (for example, 4 Fig. 7) may be phase registered or phase locked to a hologram feedback layer or other reflector or feedback layer (for example, 6 Fig. 7) using an interferometric alignment method. This results in perfect or near perfect constructive interference that maximizes the light intensity of an emissive layer. For example, light reflected from the reflector or feedback layer (6 Fig. 7) is interfered with the aerial fringe pattern used to record the refractive index profile in the holographic feedback layer (4 Fig. 7). The vertical positioning of the aerial fringe pattern may be adjusted to produce maximum constructive interference before the holographic exposure of the feedback layer (4 Fig. 7) is performed.

When holographic structures are used for both feedback layers (4 and 6, Fig. 7), the recording exposure may be carried out on both layers simultaneously with the same extended aerial fringe pattern thereby phase-registering the two structures. This phase-registrationn may be perfect or nearly perfect. The registration and phase locking provide

self-alignment of the hologram in the feedback element.

A method of producing the holograms in one embodiment will now be described in detail. In one embodiment, a glass plate with Slavich PFG-03C silver halide sensitized gelatin (SHSG) holographic emulsion on its surface is exposed to interfering plane wave beams of, for example, the 458 nm. line of an argon ion laser. The laser's output is beam split into "image" and "reference" plane wave beams of light and these are expanded to be able to cover the entire emulsion surface. The image beam then is made to impinge on the emulsion from the front along an axis normal to the glass substrate and the reference beam is made to impinge on the emulsion through the glass substrate from the back along an axis normal to the glass substrate. Thus, in one embodiment, the emulsion is exposed to the aerial fringes created by the interference of the two beams.

After the exposure, the emulsion is prehardened by immersing the plates in formaldehyde solution (formalin) for about 6 minutes. This cross-links the initially soft gelatin enough so as not to be damaged by further processing and also makes the gelatin hard enough so that air voids formed in it during the development process do not collapse. However, the interaction with the silver halide grains in the emulsion retards hardening of the gelatin around the grains leaving it relatively soft.

In one embodiment, the formalin hardening solution may comprise: 10 ml. 37% formaldehyde (formalin); 2 grams (g.) potassium bromide; 5 g. anhydrous sodium carbonate; 1 liter deionized water.

The previously exposed and prehardened plates are developed using emersion into Agfa G282c photographic developer for about 3 minutes. This converts the silver halide grains that have been exposed into silver,

converting the latent image of the fringes into a real one.

The plates are next bleached by immersion in PBU-metol bleach for approximately 15 minutes. In one embodiment, the bleach is prepared from the following ingredients: 1 g. cupric bromide; 10 g. potassium persulfate; 50 g. citric acid; 20 g. potassium bromide; 30 g. borax; 1 liter deionized water. After mixing these ingredients, 1 g. of p-methylaminophenol sulfate (metol) is dissolved in the solution. The bleach is then buffered to pH 5 using borax and then 2% chromium (III) potassium sulfate is added.

The bleach rehalogenates the silver grains in the exposed area to silver bromide, but at the same time Cr(III) ions are introduced into the gelatin immediately adjacent to the silver grains and begin cross-linking it. In one embodiment, Cr(III) is not introduced adjacent to the unexposed silver halide grains. The plates are next immersed in 60 degree C deionized water for about 10 minutes. During this time the Cr(III) finishes cross-linking the gelatin adjacent to the reconstituted silver bromide grains.

The gelatin is dehydrated by immersion in a solution of 50% industrial methylated spirit / 50% water for about 3 minutes followed by about 3 minutes immersion in undiluted industrial methylated spirit. The plates are dried in a 45 degree Celsius oven for 5 minutes.

The emulsion is then further hardened by placing the plates in a chamber with saturated formaldehyde vapor for 25 minutes. The emulsion is next fixed by immersion in a fixing bath for about 2 minutes. In one embodiment, the fixing bath comprises of: 10 g. anhydrous ammonium thiosulfate; 20 g. anhydrous sodium sulfate; 1 liter deionized water.

This fixing step removes all silver halide from the

gelatin. In the areas where the emulsion was exposed, the gelatin has been cross-linked with Cr(III) immediately around the AgBr grains and when the AgBr is removed voids are formed. In the areas where no exposure occurred, the gelatin around the Ag halide grains is soft and the voids formed immediately collapse leaving pure, homogeneous gelatin. Thus, refractive index contrast is produced between areas of pure gelatin and areas that are part gelatin / part air.

In one embodiment, the plates are washed and dehydrated by immersion in: 50% water / 50% isopropanol for 10 minutes; 100% isopropanol at 20 degrees Celsius for 10 minutes; 100% isopropanol at 45 degrees Celsius for 2 minutes. The dehydration expands the size of the voids and leaves a hard, de-swelled gelatin matrix. The plates are then dried in an oven at 45 degrees Celsius.

In one aspect, the plates may need to be sealed from humidity in the air since water will re-swell the gelatin degrading the holograms. This sealing may be done by coating a thin layer of a sealant adhesive on the hologram surface. One material that may be used is Pascofix, a cyanoacrylate material available from PASCO Industrial Adhesives in Philadelphia, PA. Photocurable epoxy sealants may also be used.

In one embodiment, an OLED structure utilized in an FE-OLED device may have the structure shown in Fig. 9, comprising the following material. It is noted that the example shown in Fig. 9 is not drawn to scale. The cathode backing 902 may comprise approximately 150 nm thick indium-tin oxide material. The cathode 904 may comprise approximately 7 nm thick aluminum material. The electron injection layer 906 comprise approximately 10 nm thick lithium fluoride material. The electron transport layer 908 may comprise approximately 35 nm thick aluminum triquinoline material. The hole blocker 910 may comprise approximately 10 nm thick bathocuproine

material. The emissive layer 912 may comprise approximately 50 nm thick H9680 material. The hole transport layer 914 may comprise approximately 75 nm thick N,N'-di(3-methylphenyl)-N,N'-diphenylbenzidine material. The hole injection layer 916 may comprise 10 nm thick copper phthalocyanine material. The anode may comprise 150 nm thick indium-tin oxide material. H9680 emissive layer may be obtained from Honeywell Specialty Chemicals in Morristown, New Jersey.

The above OLED structure may be built by successive vacuum depositions on a sealant coated surface on one of the SHSG holographic plates 920 whose preparation was described above. Then a second hologram 922 on which the sealant coat is not yet cured is placed on top of the OLED structure 902-918 and precisely positioned parallel to the bottom hologram using a piezoelectric positioner so that when the sealant cures, the two holograms 920, 922 and the OLED 902-918 are all potted together with the sealant.

In one aspect, the two sealant coatings on the two holograms in the device are at least two microns thick. The device accordingly may support multiple vertical modes. In one embodiment, the lateral dimensions of the OLED layers may be 250 microns by 250 microns.

In the above-described fabrication approach, the ITO cathode backing layer acts as a buffer between the hologram sealant and the rest of the OLED structure. In another aspect, one or more additional buffer layers may be used.

In one aspect, the one or more feedback layers in the device allow even some light emissive materials with degraded function or low efficiency to perform satisfactorily. This provides greater flexibility in selecting the other layers and elements of the device such as the emissive layer. Further, because the feedback layers in one embodiment still allow

satisfactory performance even with some light emissive materials having degraded function or low efficiency, a light emissive material may be chosen to optimize other characteristics. For example, a device that has low efficiency light emissive material because of overlap between the light emissive material absorption band and the light emissive material florescent emission band may be used if the feedback layer reflection band and thus the device emission band does not overlap the emitter absorption band.

Another example is a device with the electrodes, charge carrier injection layers, and charge carrier transport layers optimized or otherwise selected for their functions and with an emissive layer selected for optimum carrier recombination to form excitons, but which has poor quantum efficiency because of non-radiative relaxation of exciton energy. Enabling stimulated emission with feedback light from feedback layers in one embodiment may allow almost all exciton energy to be emitted as light, thus providing a highly energy efficient device.

A further example is a device with a light emissive layer including an emitter molecule derivatized with cross-linking functional groups. The cross-linking provides improved mechanical properties and make the emissive layer less fragile under high temperature conditions. With stimulated emission from feedback light this device may also be made sufficiently energy efficient.

In another aspect, the light emissive material may be chosen for a high absorption cross-section or area of interaction with the feedback light. For example, the emissive layer may be made with a material that has large molecules or a high aspect ratio to the reflected feedback light. The material may have a high polarizability at the wavelength of the feedback light

or the light emissive layer may be thicker to provide a higher interaction cross-section with the feedback light. The material may include a light emissive material in which the molecules are aligned so that their aspect ratio with the reflected feedback light has a large or maximum value or a emissive layer in which the emissive material is made more dense so that there are more molecules per unit of depth that interact with the reflected feedback light. One such material may include a metallophthalocyanine with its molecules oriented in the device such that the molecules have a very large molecular size and proper molecular aspect ratio. Orientation of the phosphor molecules may be provided by adjusting the surface energy of the underlying charged transport layer such that homogenous alignment results or by photo aligning the underlying charge transport layer. Molecules having a high cross-section of interaction with the feedback light increase the likelihood of stimulated emission. This reduces the amount of light that needs to be reflected by the feedback element in order to make stimulated emission the dominant light conversion process. In another embodiment, a patterned feedback element or layer may be fabricated using a patterned optical exposure. First, a layer of holographic photopolymer or photopolymer precursor is cast on a substrate. Next, the photopolymer or photopolymer precursor is exposed to a cross-linking light radiation through a patterned photomask. Alternatively, the patterned photomask may be omitted if the cross-linking light radiation is provided as a modulated beam.

In another embodiment, a patterned, multi-color feedback layer may be built using successive patterned exposures in the patterned feedback layers to produce areas of feedback material that reflect different colors. These patterned feedback layer areas may be

located so as to be registered with correspondingly patterned emissive material areas. The emissive material areas associated with patterned feedback layer areas reflecting a particular color band may be selected to contain emissive material that emit radiation in that color band.

In another aspect, a patterned feedback layer as described above may be fabricated by using one photomask in the image beam and one photomask in the reference beam of the holographic set-up. Fig. 10 illustrates an example of a double mask apparatus 100 that produces a patterned hologram in one embodiment. A material such as holographic emulsion 20 is exposed to the reference beam 14 and the image beam 12 via the two photomasks 18, thus exposing patterned light beams 22 to the holographic emulsion 20. In this set-up, a light source such as a laser 2 directs the laser light 4 to beam expanding optics 6. Light emitted from the beam expanding optics 6, that is expanded laser beam 8 is deflected partly and transmitted partly by a beam splitter 10. A beam splitter 8 may be a simple mirror made with a thinner coating of silver than a conventional mirror so that it does not reflect all of the light that is incident upon it, some of it being transmitted. The light transmitted is an image beam 12 which is exposed on the holographic emulsion 20 via the photomask 18. The light deflected 14 is a reference beam and is reflected by mirrors 16 and is also exposed on the holographic emulsion 20 via the other photomask 18. The resulting interference pattern recorded by the holographic emulsion 20 is the hologram.

In another aspect, one of the two photomasks 18 may be eliminated by using a high gamma photopolymer as a holographic medium 20 that has an exposure intensity threshold. Fig. 11 illustrates an example of a single mask apparatus 200 that produces a hologram in one

embodiment. In this embodiment, one photomask 18 may be used in the image beam 12. In this single photomask method, the unmasked beam (the reference beam) 14 may not have sufficient energy to exceed the exposure intensity threshold and thus to cause cross-linking in the photopolymer. The masked beam (the image beam) 12 also may not have sufficient energy to cause cross-linking in the photopolymer, although this is not required. The combination of the two beams, however, may be sufficient to cause cross-linking.

Fig. 12 is a graph 300 illustrating irradiance versus position in the double mask apparatus of Fig. 10. The graph illustrates the modulation of the exposing light from zero irradiance when optically dense features on photomasks are in place in both the image and reference beams to full irradiance when both beams are passing through apertures in the photomasks. In this set up, both photomasks are aligned to each other and to the holographic emulsion. Fig. 13 is a graph 400 illustrating irradiance versus position in a single mask apparatus of Fig. 11. This graph illustrates that in this case the combined irradiance of the exposure beams is modulated between full irradiance and some lower, non-zero value of irradiance, depending on the relative intensities of the image and reference beams. If, for example, in one embodiment the irradiance threshold of the holographic emulsion, portrayed in graph 500 in Figure 14, is higher in irradiance than the low value of irradiance modulation in Figure 13, then patterned holograms may be successfully recorded. This set-up does not require the registration of two masks.

A holographic feedback layer may be produced by coating a layer of photosensitive holographic recording material onto a device substrate. The material is then exposed to light so as to produce a pattern, such as a plane wave interference pattern, down into the depth of

the layer such that the level of exposure of the recording material is uniform in all directions in the plane, but varies in uniformity sinusoidally along the axis normal to the layer plane. A plane wave interference pattern may be produced by generating a plane wave of the desired wavelength, splitting it into two components, phase delaying one component relative to the other, then simultaneously exposing the recording film to both components. This process records the hologram of a plane wave source. The recording film or material is sensitized so that when it is exposed to light a cross-linking reaction occurs causing the refractive index to change. For instance, the Slavich material contains sensitizing dyes that render it panchromatic. This in one embodiment may be one way of recording the desired cyclic variation of refractive index in the feedback layer.

In another embodiment, an emissive material with broader fluorescent emission bands may be combined with a feedback element optimized to allow single mode emission of a desired wavelength to constrain the emission bandwidth of the emissive material. As previously described, feedback elements may cause stimulated emission in the emissive element. The stimulated emission may be limited to the same wavelength band or bands as the reflection band or bands of light of the feedback element. Thus, a broadband emissive material may be used with a narrow band reflective feedback element to produce a narrow wavelength band of light, for example, with substantially no loss of energy conversion efficiency. In one aspect, this provides a great deal of design freedom in emissive material selection. For example, in devices with emissive materials in which the spectral emission band overlaps the absorption band such that self-absorption normally occurs, the narrow band

reflective feedback element may be chosen to have a peak wavelength that does not overlap the emissive material absorption band. In this way, for example, emissive material self-absorption may be eliminated and a more energy efficient device may result. Similarly, in another embodiment, a precise placement of the feedback layer reflection band may be used to avoid absorption bands of other device layers.

In one aspect, an ability to tune the device output away from a material absorption band implies that otherwise highly useful emissive materials and other device materials that are normally rejected because of self-absorption or incompatibility with absorption bands of other device layers may now be used in devices with feedback layers. Another use of this effect is to have the feedback element have two or more separate spectral reflection bands. Where the separate reflection bands each overlap a portion of the broad emission spectrum of an emitter material, multiple wavelength bands of light may be emitted from the same region of the emissive material.

Another use may be one in which separate reflection bands are patterned in different areas of the feedback layers. For example, Fig. 5 illustrates a pixelated device 30 with a broadband emissive layer 32 and two pixelated feedback layers 34 in one embodiment. For instance, for an emitter that radiated light of reasonable intensity between 520 nm. and 700 nm., a checker board pattern in the feedback layers is patterned in which the refractive index alternation in the layers is equivalent to a wavelength of 520 nm. Then the complementary checkerboard pattern is patterned so that the index profile corresponds to a wavelength of 650 nm. In this way, the device emits a checker board pattern of light with the alternating squares (pixels) colored red and green.

In one embodiment, the pixelated feedback layers 34 include first areas 36 and second areas 38. The first areas 36 reflect light of a first wavelength while the second areas 38 reflect light of a second wavelength. The first areas 36 of the pixelated feedback layers 34 cause stimulated emission in the broadband emissive layer 32 only or substantially only at the first wavelength. Similarly, the second areas 38 of the pixelated feedback layers 34 cause stimulated emissions in the broadband emissive layer 32 only or substantially only at the second wavelength.

Thus in one embodiment, a multi-colored device may be made without providing separate emissive materials for each of the first and second wavelengths. This may reduce the processing steps required for fabrication of the broadband emissive layer 32. In one embodiment, if refractive index profiles are recorded into the pixelated feedback layers 34, the first and second areas 36, 38 may be formed at the same time to further reduce the number of fabrication steps and complexity of the pixelated device 30. Further, although Fig. 5 illustrates two wavelengths, three of more wavelengths of light may be stimulated from the broadband emissive layer 32. Such a pixelated device 30 may be used to display digital, alphanumeric, or graphic information. For example, the pixelated device 30 may be used to create a wide color gamut in graphic displays without emitting unwanted infrared and ultraviolet wavelengths of light.

In another embodiment, both the feedback layers and the emitters may be patterned. For instance, red, green, and blue emitters may be patterned in pixels with overlaid feedback layer patterned red, green, and blue respectively. In another embodiment, one or more feedback layers may be formed from a photosensitive material having a hologram of a plane wave written on

the material using polarized light. The light may be plane polarized along any axis perpendicular to its direction of propagation or alternatively the light may be right circularly, left circularly, or elliptically polarized light. In these embodiments, the feedback layer returns polarized feedback light into the resonant cavity of the OLED or LED device. In one embodiment, this polarized feedback light stimulates emission of light from the emissive layer that has an identical polarization state. Thus, a substantial portion or all of the light produced by the OLED or LED device may have a polarization state identical or substantially identical to the original light used to write the hologram in the feedback layer.

In one embodiment, one or more polarized holographic feedback layers may be written with a patterned exposure through a photomask. In one aspect, separate areas of an emissive device may be constrained to emit light having different polarization states by using a series of patterned exposures with light of differing polarization states. For example, feedback layers patterned in a pixelated rectangular matrix may have alternating pixels with orthogonal linear axes of polarization.

In another embodiment, one or more feedback layers may be formed with materials with chiral centers and used as photonic crystal feedback layers, for example, if the materials have one-dimensional photonic crystal refractive index profile. For instance, homogenously aligned cholesteric liquid crystals have chiral centers that induce helical structure such that the one-dimensional photonic crystal refractive index profile results. This is illustrated in Fig. 6. The polarization direction of plane polarized light is not affected by passage through the medium when the pitch of the helical structure of the material is sufficiently

short. In this case, light with an axis of propagation parallel to the helical axis sees a sinusoidally varying refractive index. This structure may be formed from a polymer film produced by polymerizing cholesteric reactive mesogen monomers.

In another embodiment, one or more conventional OLED conductive and semiconductive layers may be fabricated so as to allow them to also act as a photonic crystal structure, for example, in addition to their conventional functionalities in an OLED. For example, the photonic crystal structure of the feedback layers may extend into the OLED structure itself. For instance, the materials used to build up the hole injection, hole transport, emission, electron transport, and electron injection layers in an OLED may have chiral liquid crystalline phases or structures of the same pitch as the refractive index alternation in the feedback layers. These materials may be derivatized with cross-linking moieties and sensitized such that interference patterns may be recorded in them. In this way feedback layer holograms may be extended into the OLED.

A useful aspect of modifying the optical properties of OLED component layers so as to extend the photonic crystal structure into the OLED structure is that, as was described above, to produce a defect-mode laser, the defect zone in which the OLED emitter is located may have a thickness of less than the equivalent of one wavelength of light. For example, this aspect is useful in the case of blue FE-OLEDs because for blue light a thickness equivalent to one wavelength is smaller than the combined thicknesses of the various OLED functional layers. Thus, in one embodiment, a way of designing a defect-mode device may involve extending the photonic crystal structures into OLED as described above.

The embodiments described above are illustrative

examples and it should not be construed that the present invention is limited to these particular embodiments. For example, although OLED devices were used as examples of emissive devices, other luminescent material or structures may be used, not limited to OLEDs. Further, although refractive index profiles, direction of light, etc. were described as being "normal" to a plane, it should be understood that they need not be exactly normal, rather in a close range of being normal or substantially normal. Accordingly, the embodiments described in this application also may include cases in which they are about normal or substantially normal to a plane. Further, various components and aspects described with reference to different embodiments are interchangeable among different embodiments, and are not limited to one particular embodiment. Thus, various changes and modifications may be effected by one skilled in the art without departing from the spirit or scope of the invention as defined in the appended claims.

CLAIMS

We claim:

1. A feedback enhanced light emitting device, comprising:

a first feedback layer adapted to receive and reflect light;

a second feedback layer adapted to receive and reflect light, at least one of the first feedback layer and the second feedback layer having a refractive index profile that at least in part varies periodically and continuously along an axis normal or substantially normal to a plane of a respective feedback layer; and

an emissive layer disposed between the first feedback layer and the second feedback layer.

2. A feedback enhanced light emitting device, comprising:

a first feedback layer adapted to receive and reflect light;

a second feedback layer adapted to receive and reflect light, at least one of the first feedback layer and the second feedback layer having a refractive index profile that at least in part varies periodically and continuously along an axis normal or substantially normal to a plane of the first feedback layer, at least one of the first feedback layer and the second feedback layer adapted to reflect one or more predetermined wavelength bands of light at least along an axis normal or substantially normal to the plane of a respective feedback layer; and

an emissive layer disposed between the first feedback layer and the second feedback layer, the emissive layer adapted to emit light, the emissive layer further adapted to provide stimulated emission caused by the one or more predetermined wave length bands

of light reflected from one or more of the first feedback layer and the second feedback layer.

3. The device of claim 1, wherein the first feedback layer or the second layer or both the first feedback layer and the second layer comprises a hologram.

4. The device of claim 1, wherein the first feedback layer or the second layer or both the first feedback layer and the second layer comprises a hologram of a plane wave light source.

5. The device of claim 1, wherein the emissive layer comprises an organic luminescent material.

6. The device of claim 1, wherein the emissive layer comprises at least one or more of, a cross-linked organic luminescent material, a cross-linked polymer luminescent material, a luminescent material comprising molecules having molecular weight range between that of a small molecule to a polymer, a small molecule luminescent material dissolved in a polymer host, a fluorescent material, a phosphorescent material, an organic and inorganic composite luminescent material, an inorganic luminescent material, and a liquid crystalline luminescent material.

7. The device of claim 1, further comprising:

a first electrode disposed between the first feedback layer and the emissive layer; and

a second electrode disposed between the second feedback layer and the emissive layer.

8. The device of claim 7, wherein the first electrode is an anode and the second electrode is a

cathode.

9. The device of claim 7, wherein the first electrode is a cathode and the second electrode is an anode.

10. The device of claim 7, further comprising:

one or more buffer layers disposed between one or both of the first and the second feedback layers and one or both of the first electrode and the second electrode.

11. The device of claim 10, wherein the one or more buffer layers comprise at least transparent dielectric material.

12. The device of claim 10, wherein the one or more buffer layers are used to hermetically isolate the device from atmospheric contamination.

13. The device of claim 10, wherein the one or more buffer layers are disposed to provide spacing between the first feedback layer and the second feedback layer such that constructive interference and stimulated emission occur at one or more selected wavelengths.

14. The device of claim 1, further comprising a hole injection layer disposed between the first feedback layer and the emissive layer.

15. The device of claim 1, further comprising an electron injection layer disposed between the second feedback layer and the emissive layer.

16. The device of claim 1, further comprising a hole transport layer disposed between the hole injection layer and the emissive layer.

17. The device of claim 1, further comprising an electron transport layer disposed between the electron injection layer and the layer of light emissive organic material.

18. The device of claim 1, wherein at least one of first feedback layer and the second feedback layer comprises at least one or more of a plane mirror, a multilayer dielectric distributed Bragg reflector, a specular surface of an electrode, and a non-photonic crystal reflector.

19. The device of claim 1, wherein both the first feedback layer and the second feedback layer transmit no light at a peak wavelength of their spectral reflection bands and the light emissive material radiates light into band-edge laser modes.

20. The device of claim 1, wherein a level of light fed back from the first feedback layer and the second feedback layer is sufficient to initiate laser action.

21. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer comprises one or more of tuned thickness and tuned refractive index contrast to optimize an amount of light fed back into the emissive layer.

22. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer comprises at least one or more discontinuities in the continuously varying refractive index profile.

23. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer

comprises a plurality of individual feedback layer refractive index profiles.

24. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer comprises refractive index profiles that have superimposed refractive index profiles with non-reflective functions.

25. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer comprises refractive index profiles having a dominant periodicity n/2 times a selected wavelength of the feedback light, where n is an integer.

26. The device of claim 1, wherein one or both of the first feedback layer and the second feedback layer is thinned in one or both of physical thickness and optical thickness to enable light to escape the device.

27. The device of claim 4, wherein optical thickness of one or both of the first feedback layer and the second feedback layer is thinned by varying a holographic exposure and a resulting refractive index contrast of the hologram.

28. The device of claim 1, further including one or more layers disposed between the first feedback layer and the second feedback layer, the one or more layers formed with a structure that is enabled to continue a refractive index alternation that comprises a photonic crystal structure in one or both of the first feedback layer and the second feedback layer.

29. The device of claim 28, wherein the one or

more layers comprise at least one or more of electrode, charge carrier injection layer, charge carrier transport layer, carrier blocking layer, and the emissive layer.

30. The device of claim 28, wherein the refractive index alternation is produced holographically by fabricating the one or more layers using one or more of a photopolymer and photosensitive material and exposing the one or more of a photopolymer and photosensitive material to light.

31. The device of claim 28, wherein the refractive index alternation is produced by at least one or more of a cholesteric and chiral liquid crystal structure in a material used to fabricate the one or more layers.

32. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback layer and the second feedback layer comprises at least a material having at least a sinusoidally varying refractive index profile.

33. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback layer and the second feedback layer comprises a plurality of regions adapted to reflect a plurality of predetermined wavelength bands of light, with at least one of the plurality of regions adapted to reflect a predetermined spectral band of light centered on a wavelength different from a predetermined spectral band of light centered on a wavelength reflected by another one of the plurality of regions.

34. The device of claim 33, wherein one of the first feedback layer and the second feedback layer comprises at least a photonic crystal structure and a

plurality of regions adapted to reflect a plurality of predetermined wavelength bands of light, with at least one of the plurality of regions adapted to reflect a predetermined spectral band of light centered on a wavelength different from a spectral band of light centered on a predetermined wavelength reflected by another one of the plurality regions, and with the plurality of regions in the first feedback layer registered to a corresponding plurality of regions in the second feedback layer reflecting spectral bands centered on the same wavelengths of light.

35. The device of claim 33, wherein the emissive layer comprises at least a plurality of regions adapted to emit a plurality of predetermined wavelength bands of light, with at least one of the plurality of regions adapted to emit a predetermined wavelength band of light different from a predetermined wavelength band of light reflected by another one of the plurality regions, and with each of the plurality of regions registered to corresponding regions in at least one of the first feedback layer and the second feedback layer with spectral reflection bands of light that at least in part overlap the corresponding emitter spectral emission bands.

36. The device of claim 35, wherein two or more of the plurality of regions in the emissive layer registered to corresponding regions in the feedback layers adapted to reflect a plurality of predetermined spectral bands of light centered on different wavelengths is adapted to emit predetermined different wavelength bands of light from the same broad spectral band emissive material that at least in part overlaps of all of the corresponding emitter spectral emission bands.

37. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises a hologram having a plurality of refractive index profiles superpositioned in the hologram.

38. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises a hologram having a plurality of refractive index profiles corresponding through Bragg's law to a plurality of wavelengths of light superpositioned in the hologram.

39. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises one or more regions having constant refractive index.

40. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises material having a photonic crystal structure.

41. The device of claim 40 wherein both the first feedback layer and the second feedback layer combine to form at least in part a continuous photonic crystal structure.

42. The device of claim 41, wherein both the first feedback layer and the second feedback layer transmit substantially no light emitted by the emissive layer at the peak wavelengths of their spectral reflection bands and the emissive layer radiates light into band-edge light propagation modes of the photonic crystal.

43. The device of claim 42, wherein the emissive

layer comprises an organic luminescent material.

44. The device of claim 42, wherein the emissive layer comprises at least one or more of, a cross-linked organic luminescent material, a cross-linked polymer luminescent material, a luminescent material comprising molecules having molecular weight range between that of a small molecule to a polymer, a small molecule luminescent material dissolved in a polymer host, a fluorescent ematerial, a phosphorescent material, an organic and inorganic composite luminescent material, an inorganic luminescent material and a liquid crystalline luminescent material.

45. The device of claim 42, further comprising:

a first electrode disposed between the first feedback layer and the emissive layer; and

a second electrode disposed between the second feedback layer and the emissive layer.

46. The device of claim 45, wherein the first electrode is an anode and the second electrode is a cathode.

47. The device of claim 45, wherein the first electrode is a cathode and the second electrode is an anode.

48. The device of claim 42, wherein a level of light fed back from the first feedback layer and the second feedback layer is sufficient to initiate laser action.

49. The device of claim 47, further comprising:

one or more buffer layers disposed between the a feedback layer and one or both of the first electrode

and the second electrode.

50. The device of claim 49, wherein the one or more buffer layers comprises at least transparent dielectric material.

51. The device of claim 49, wherein the one or more buffer layers is used to hermetically isolate the device from atmospheric contamination.

52. The device of claim 49, wherein the one or more buffer layers is disposed to provide spacing between the first feedback layer and the second feedback layer such that constructive interference and stimulated emission occur at a selected wavelength or wavelengths.

53. The device of claim 42, further comprising a hole injection layer disposed between the first feedback layer and the emissive layer.

54. The device of claim 42, further comprising an electron injection layer disposed between the second feedback layer and the emissive layer.

55. The device of claim 42, further comprising a hole transport layer disposed between the hole injection layer and the emissive layer.

56. The device of claim 42, further comprising an electron transport layer disposed between the electron injection layer and the layer of light emissive organic material.

57. The device of claim 40, wherein the light emissive layer comprises a defect in a continuous photonic crystal formed by the first feedback layer and

the second feedback layer.

58. The device of claim 57, wherein the defect comprises a phase-slip in spatial phase along one dimension of the photonic crystal of less than one wavelength.

59. The device of claim 57, wherein the light emitted from the light emissive layer emanates into a defect mode.

60. The device of claim 59, wherein the emissive layer comprises an organic luminescent material.

61. The device of claim 59, wherein the emissive layer comprises at least one or more of, a cross-linked organic luminescent material, a cross-linked polymer luminescent material, a luminescent material comprising molecules having molecular weight range between that of a small molecule to a polymer, a small molecule luminescent material dissolved in a polymer host, a fluorescent material, a phosphorescent material, an organic and inorganic composite luminescent material, an inorganic luminescent material and a liquid crystalline luminescent material.

62. The device of claim 59, further comprising:

a first electrode disposed between the first feedback layer and the emissive layer; and

a second electrode disposed between the second feedback layer and the emissive layer.

63. The device of claim 62, wherein the first electrode is an anode and the second electrode is a cathode.

64. The device of claim 62, wherein the first electrode is a cathode and the second electrode is an anode.

65. The device of claim 59, wherein a level of light fed back from the first feedback layer and the second feedback layer is sufficient to initiate laser action.

66. The device of claim 62, further comprising:

a buffer layer disposed between one or both of the first and the second feedback layers and one or both of the first electrode and the second electrode.

67. The device of claim 66, wherein the buffer layer comprises at least transparent dielectric material.

68. The device of claim 66, wherein the buffer layer is used to hermetically isolate the device from atmospheric contamination.

69. The device of claim 66, wherein the buffer layer is disposed to provide spacing between the first feedback layer and the second feedback layer such that constructive interference and stimulated emission occur at a selected wavelength or wavelengths.

70. The device of claim 59, further comprising a hole injection layer disposed between the first feedback layer and the emissive layer.

71. The device of claim 59, further comprising an electron injection layer disposed between the second feedback layer and the emissive layer.

72. The device of claim 59, further comprising a hole transport layer disposed between the hole injection layer and the emissive layer.

73. The device of claim 59, further comprising an electron transport layer disposed between the electron injection layer and the layer of light emissive organic material.

74. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer partially transmits light received from the emissive layer.

75. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises one or more of chiral and cholesteric liquid crystals.

76. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises opals, particulate agglomerates having structures akin to a crystalline lattice, middle phase lyotropic liquid crystals in a fluid or polymerized state, and self-assembled block copolymers.

77. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises a dielectric material of continuously varying composition.

78. The device of claim 1, wherein the first feedback layer and the second feedback layer are phase-locked or phase-registered.

79. The device of claim 78, wherein the phase-locking or phase-registration is performed interferometrically.

80. The device of claim 1, wherein the first feedback layer and the second feedback layer are formed holographically and simultaneously using one simultaneous exposure to an array of interference fringes formed by two beams of plane polarized light.

81. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises a hologram of plane waves written with linearly, circularly, or elliptically polarized light.

82. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer comprises a hologram fabricated by recording a refractive index profile in one or more of dichromated gelatin, dichromated emulsions, silver halide gelatine, silver halide emulsions, photopolymer material, positive photosensitive material, negative photosensitive material, and other photosensitive material.

83. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the first feedback and the second feedback layer is formed with a material with chiral centers.

84. The device of claim 1, wherein the emissive layer comprises transparent electroluminescent material.

85. The device of claim 1, wherein the first feedback layer or the second feedback layer or both the

first feedback and the second feedback layer comprise material patterned to reflect different wavelength bands of light.

86. The device of claim 1, wherein the emissive layer is patterned to emit different wavelength bands of light.

87. The device of claim 1, wherein the emissive layer comprises an electroluminescent material having spectral emission band that overlaps reflection bands of the first feedback layer and the second feedback layer.

88. The device of claim 1, wherein all light emitted by the device occupies a single light propagation mode.

89. The device of claim 88, wherein spacing between the first feedback layer and the second feedback layer is equivalent to $\lambda/2$ excluding phase shifts due to reflection, λ being a wavelength of the light in the single light propagation mode.

90. The device of claim 1, wherein light emitted by the device occupies two or more light propagation modes.

91. The device of claim 90, wherein one or both of the device substrate and cover are transparent and are used as spacers between the two feedback layers providing proper spacing between the layers to yield the desired laser mode spacing and spectral location.

92. The device of claim 1, further including:

a substrate on which one of the first feedback

layer and the second feedback layer is disposed.

93. The device of claim 92, wherein the substrate comprises at least one or more of a flexible material, a rigid material, a glass, a metal, and a semiconductor material.

94. The device of claim 93, wherein the flexible material comprises one or more of a film of polyethylene terephthalate, (PET), polyethylene naphthalate (PEN), bisphenol A polycarbonate, and another engineering polymer.

95. The device of claim 1, further including:

a cover disposed on at least one of the first feedback layer and the second feedback layer.

96. The device of claim 1, wherein the refractive index profile comprises a profile intermediate between a square wave profile and a sinusoidal profile.

97. The device of claim 1, wherein a spectral reflection band of one or both the first feedback layer and the second feedback layer are chosen so as to generate stimulated emission that substantially overlaps neither a spectral excitation band nor a spectral absorption band of the emissive layer.

98. The device of claim 1, wherein a reflection band of one or both of the first feedback layer and the second feedback layer is spectrally narrower than an emission band of the emissive layer.

99. The device of claim 4, wherein the emissive layer comprises inorganic semiconductor material.

100. A method of fabricating a feedback element coupled to an emissive element in a device for emitting light, comprising:

disposing a layer of polymer on a substrate; and

exposing the polymer to light to record one or more interference patterns in the polymer.

101. The method of claim 100, further comprising cross-linking the polymer.

102. A method of fabricating a feedback layer, comprising:

successively exposing holographic patterns on holographic material using photomasks in both image and reference beams of a holographic set up to form a plurality of regions reflecting a plurality of different wavelength bands of light.

103. A method of fabricating a feedback layer, comprising:

successively exposing holographic patterns on holographic material using a single photomask in one of an image beam and a reference beam to form a plurality of regions reflecting a plurality of different wavelength bands of light, the holographic material having a selected irradiance threshold of exposure such that energy of an unpatterned beam alone does not cause refractive index change in the material.

104. A method of fabricating a feedback enhanced light emitting device, comprising:

forming a substrate;

forming a first feedback layer;

forming a first electrode on the first feedback layer;

forming an emissive layer on the first electrode;

forming a second electrode on the emissive layer; and

forming a second feedback layer on the second electrode.

105. The method of claim 104, wherein by the emissive layer is formed by forming a layer of photo-cross-linkable material on the first electrode and then exposing it to light to cross-link it.

106. The device of claim 7, wherein the cathode comprises a transparent low work function material.

107. The device of claim 7, wherein the cathode comprises a first, very thin metal layer disposed towards the emissive layer and a second thicker layer comprising a transparent conductive material such as indium-tin oxide.

108. The device of claim 7, wherein the anode comprises a transparent high work function material.

109. The device of claim 79, wherein the second feedback layer is formed holographically using an aerial interference fringe pattern phase-locked or phase-registered to the first feedback layer interferometrically.

110. The device of claim 91, wherein a t ransparent spacer is fabricated between the first feedback layer and the second feedback layer to provide selected spacing between the first feedback layer and the second feedback layer to yield the selected laser mode spacing and spectral location.

111. The device of claim 42, further including one

or more layers disposed between the first feedback layer and the second feedback layer, the one or more layers formed with a structure that is enabled to continue a refractive index alternation that comprises a photonic crystal structure in one or both of the first feedback layer and the second feedback layer.

112. The device of claim 111, wherein the one or more layers comprise at least one or more of electrode, charge carrier injection layer, charge carrier transport layer, carrier blocking layer, and the emissive layer.

113. The device of claim 57, further including one or more layers disposed between the first feedback layer and the second feedback layer, the one or more layers formed with a structure that is enabled to continue a refractive index alternation that comprises a photonic crystal structure in one or both of the first feedback layer and the second feedback layer.

114. The device of claim 113, wherein the one or more layers comprise at least one or more of electrode, charge carrier injection layer, charge carrier transport layer, carrier blocking layer, and the emissive layer.

115. The device of claim 42, wherein a level of light fed back from the first feedback layer and the second feedback layer is sufficient to initiate laser action.

116. The device of claim 57, wherein a level of light fed back from the first feedback layer and the second feedback layer is sufficient to initiate laser action.

117. A feedback enhanced light emitting device,

comprising:

a first means for reflecting light;

a second means for reflecting light, at least one of the first means and the second means having a refractive index profile that at least in part varies periodically and continuously along an axis normal or substantially to a plane of a respective first and/or second means; and

a third means for emitting light at least as a result of receiving the light reflected by at least one of the first means and the second means.

118. A feedback enhanced light emitting device, comprising:

a hologram layer;

a reflector layer; and

at least a luminescent material disposed between the hologram layer and the reflector layer.

119. The device of claim 112, wherein the reflector layer comprises at least a second hologram layer.

120. A feedback enhanced light emitting device, comprising:

a photonic crystal structure layer;

a reflector layer; and

at least a luminescent material disposed between the photonic crystal structure layer and the reflector layer.

121. A feedback enhanced light emitting device, comprising:

a first reflector;

a second reflector;

and at least a luminescent material disposed

between the first and the second reflector layers, wherein the first reflector and the second reflector combine to form at least in part a continuous photonic crystal structure.

122. A feedback enhanced light emitting device, comprising:

a first reflector;

a second reflector;

and at least a luminescent material disposed between the first and the second reflector layers, the at least a luminescent material comprising a defect in a continuous photonic crystal formed by the first reflector and the second reflector.

123. A feedback enhanced light emitting device, comprising:

a first feedback layer adapted to receive and reflect light;

a second feedback layer adapted to receive and reflect light, at least one of the first feedback layer and the second feedback layer having a refractive index profile that varies periodically and continuously along an axis normal or substantially normal to a plane of a respective feedback layer; and

an emissive layer disposed between the first feedback layer and the second feedback layer.

124. The device of claim 1, wherein a distance between the first feedback layer and the second feedback layer is such that the space between the feedback layers comprise a cavity in which light of one or more desired wavelengths constructively interfere.

125. The device of claim 1, wherein light reflected by one or both of the first feedback layer and

the second feedback layer stimulates emission of light from the emissive layer.

126. The device of claim 125, wherein the stimulated emission of light results in substantial collimation of light emitted by the device.

127. The device of claim 125, wherein the stimulated emission of light results in laser action.

FIG. 1

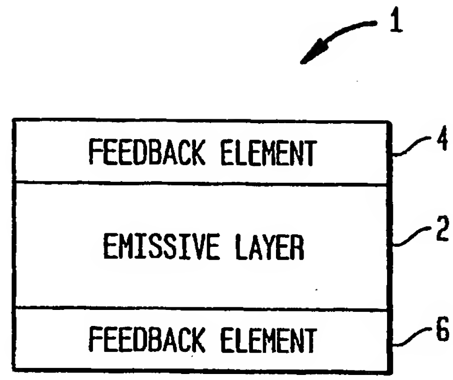

1
FEEDBACK ELEMENT
4
EMISSIVE LAYER
2
FEEDBACK ELEMENT
6

FIG. 2

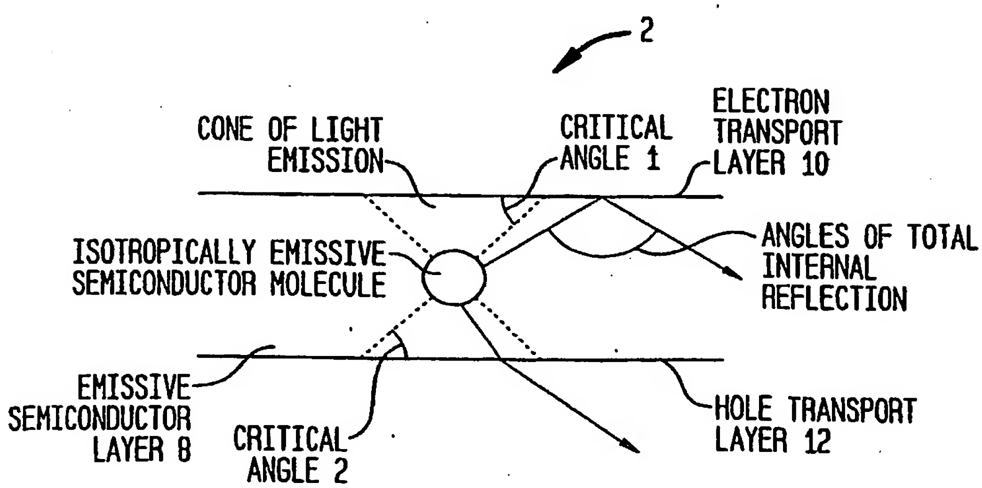

2
CONE OF LIGHT EMISSION
CRITICAL ANGLE 1
ELECTRON TRANSPORT LAYER 10
ISOTROPICALLY EMISSIVE SEMICONDUCTOR MOLECULE
ANGLES OF TOTAL INTERNAL REFLECTION
EMISSIVE SEMICONDUCTOR LAYER 8
CRITICAL ANGLE 2
HOLE TRANSPORT LAYER 12

FIG. 3

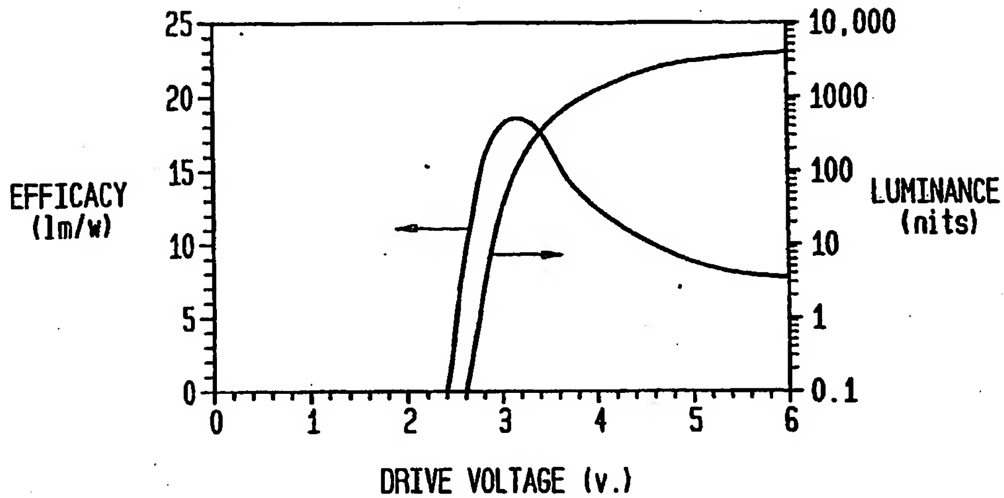

25
20
15
10
5
0
EFFICACY (lm/w)
10,000
1000
100
10
1
0.1
LUMINANCE (nits)
0
1
2
3
4
5
6
DRIVE VOLTAGE (v.)

FIG. 4

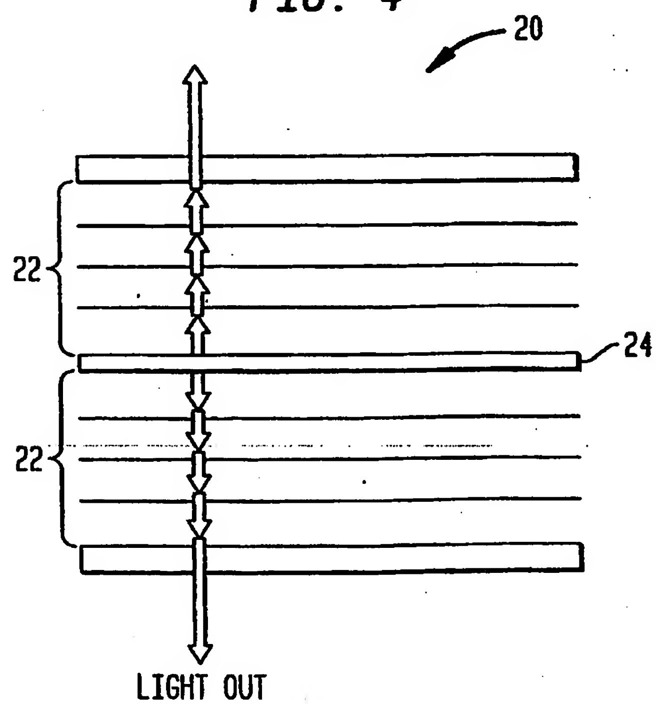

20
22
24
22
LIGHT OUT

FIG. 5

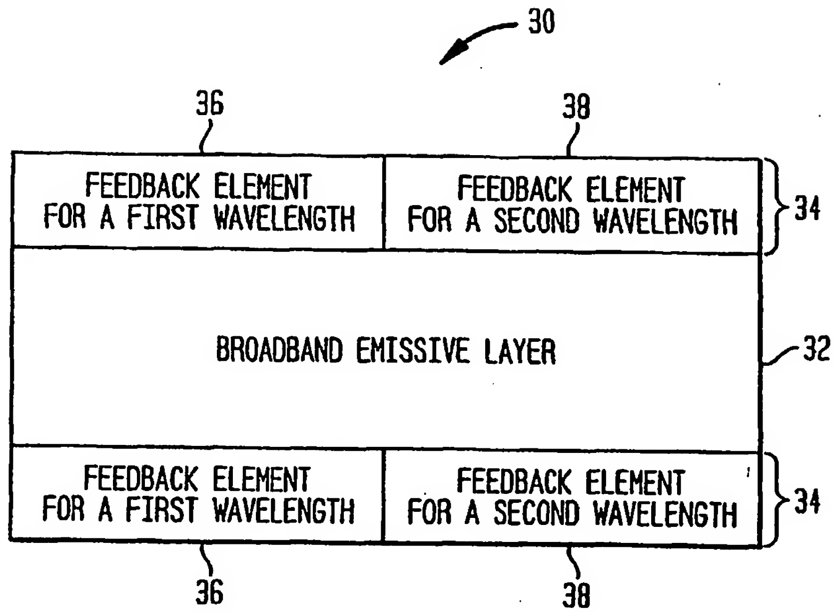

30
36
38
FEEDBACK ELEMENT FOR A FIRST WAVELENGTH
FEEDBACK ELEMENT FOR A SECOND WAVELENGTH
34
BROADBAND EMISSIVE LAYER
32
FEEDBACK ELEMENT FOR A FIRST WAVELENGTH
FEEDBACK ELEMENT FOR A SECOND WAVELENGTH
34
36
38

FIG. 6

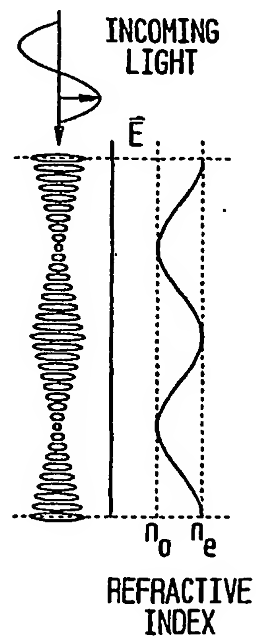

INCOMING LIGHT
E
n_o n_e
REFRACTIVE INDEX

FIG. 7

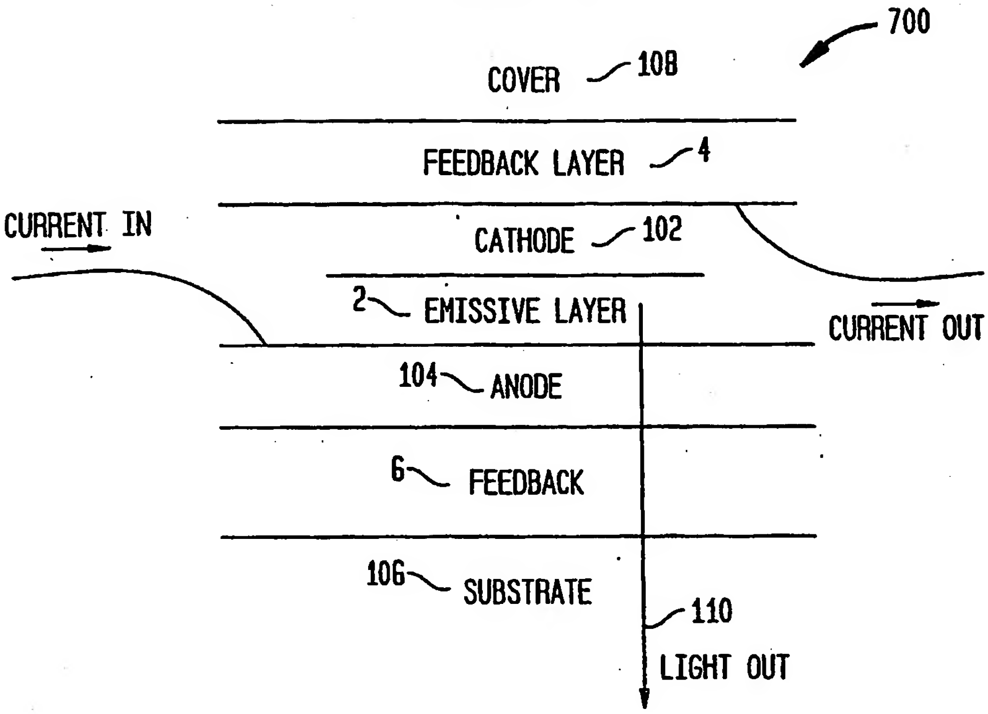

700
COVER
108
FEEDBACK LAYER
4
CURRENT IN
CATHODE
102
2
EMISSIVE LAYER
CURRENT OUT
104
ANODE
6
FEEDBACK
106
SUBSTRATE
110
LIGHT OUT

FIG. 8

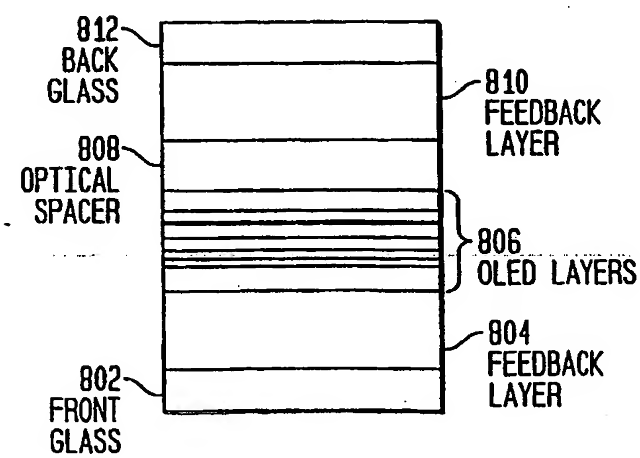

812
BACK
GLASS
810
FEEDBACK
LAYER
808
OPTICAL
SPACER
806
OLED LAYERS
804
FEEDBACK
LAYER
802
FRONT
GLASS

FIG. 9

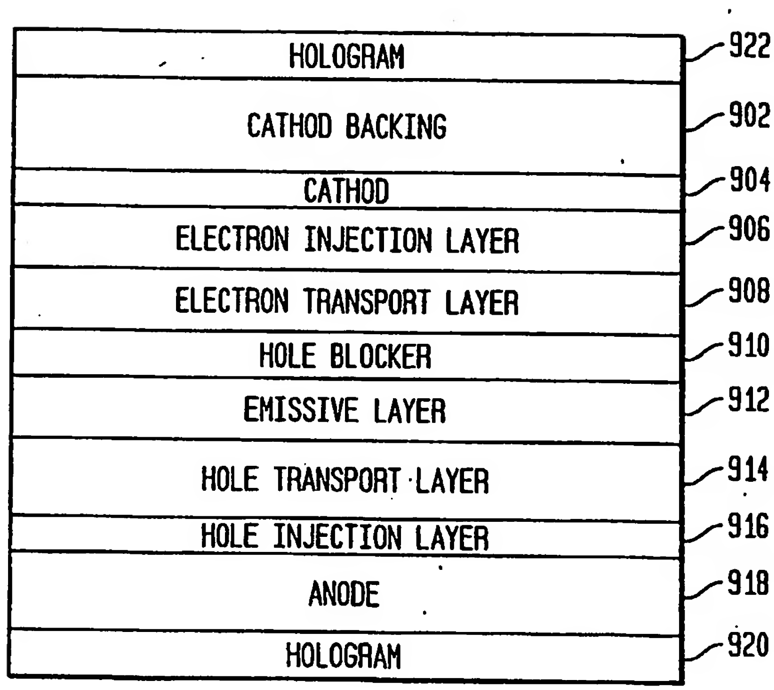

HOLOGRAM
922
CATHOD BACKING
902
CATHOD
904
ELECTRON INJECTION LAYER
906
ELECTRON TRANSPORT LAYER
908
HOLE BLOCKER
910
EMISSIVE LAYER
912
HOLE TRANSPORT LAYER
914
HOLE INJECTION LAYER
916
ANODE
918
HOLOGRAM
920

FIG. 10

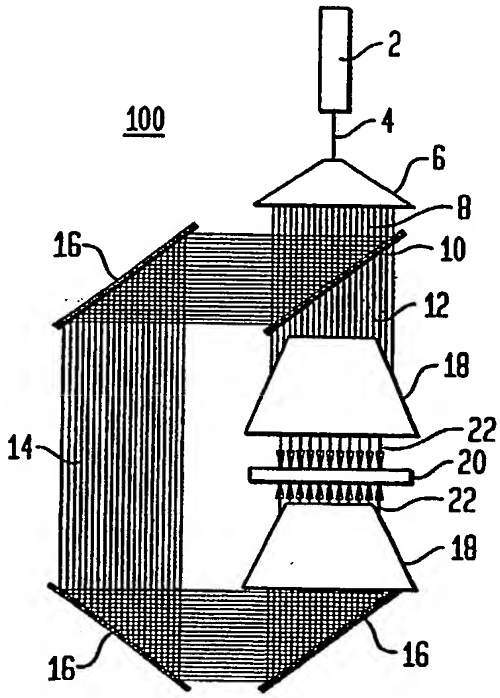


FIG. 11

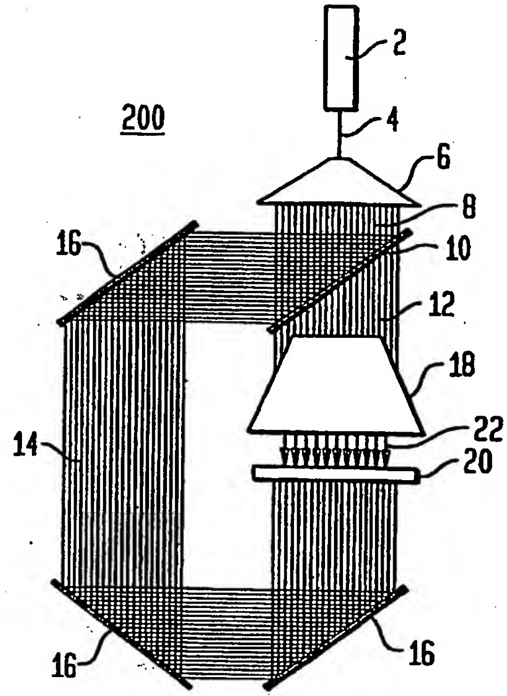


FIG. 12

300

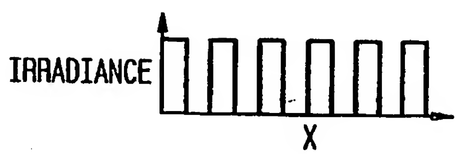


FIG. 13

400

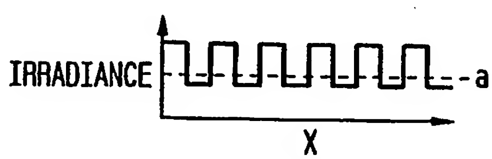
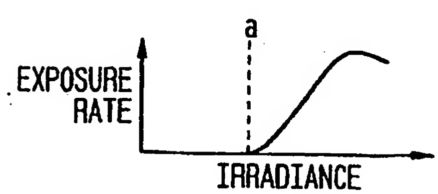


FIG. 14

500



SUBSTITUTE SHEET (RULE 26)

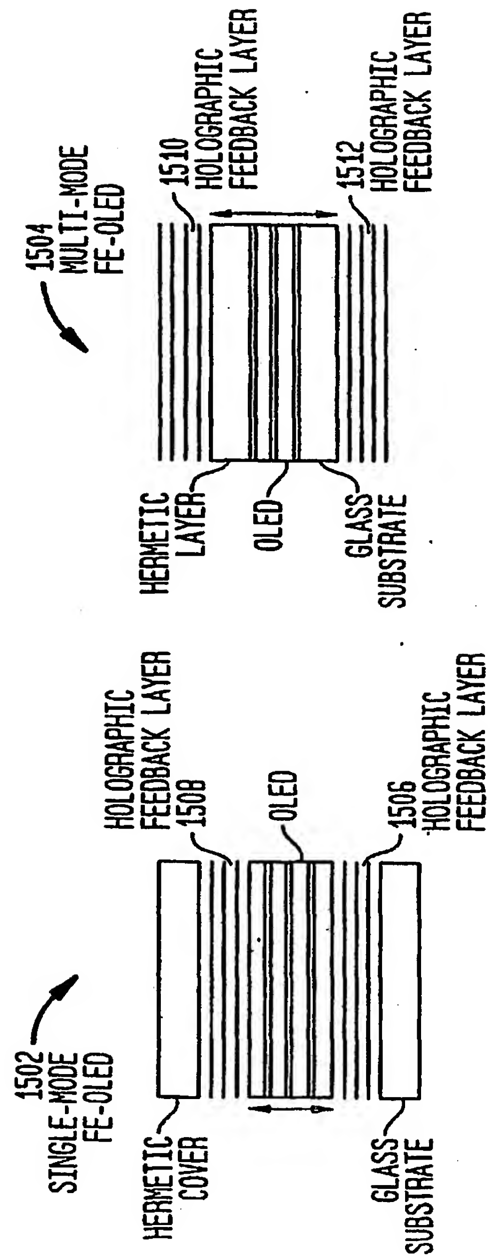

1504
MULTI-MODE
FE-OLED
1510
HOLOGRAPHIC
FEEDBACK LAYER
1512
HOLOGRAPHIC
FEEDBACK LAYER
HERMETIC
LAYER
OLED
GLASS
SUBSTRATE
1502
SINGLE-MODE
FE-OLED
HOLOGRAPHIC
FEEDBACK LAYER
1508
OLED
1506
HOLOGRAPHIC
FEEDBACK LAYER
HERMETIC
COVER
GLASS
SUBSTRATE

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/14600

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H05B 33/22

US CL : 313/498

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 313/498, 504, 504, 509, 113; 445/24

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,142,192 A (TAKAHASHI et al) 25 August 1992 (25.08.1992), column 3, line 9-50.	1-127
X	US 5,559,400 A (NAKAYAMA et al) 24 September 1996 (24.09.1996), column 6, lines 11-60.	1-127
X	US 5,847,506 A (NAKAYAMA et al) 08 December 1998 (08.12.1998), column 3, line 61 to column 4, line 45.	1-127
X	US 6,072,275 A (KOBASHI) 06 June 2000 (06.06.2000), column 4, line 47 to column 5, line 28.	1-127
X	US 6,075,317 A (KEYSER et al) 13 June 2000 (13.06.2000), column 6, line 20-52.	1-127
X	US 6,091,195 A (FORREST et al) 18 July 2000 (18.07.2000), column 4, lines 30-67.	1-127
X	US 6,097,147 A (BALDO et al) 01 August 2000 (01.08.2000), column 3, line 61 to column 4, line 36.	1-127
X	US 6,142,643 A (ARAKI et al) 07 November 2000 (07.11.2000), column 2, line 20-54.	1-127
X	US 6,259,423 B1 (TOKITO et al) 10 June 2001 (10.06.2001), column 5, lines 14-50.	1-127

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

16 July 2003 (16.07.2003)

Date of mailing of the international search report

09 SEP 2003

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

Facsimile No. (703)305-3230

Authorized officer

Sandra O'Shea Diane Smith for

Telephone No. (703)308-0956

Form PCT/ISA/210 (second sheet) (July 1998)

PCT/US03/14600

INTERNATIONAL SEARCH REPORT

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, P	US 6,433,355 B1 (RIESS et al) 13 August 2002 (13.08.2002), column 10 to column 11.	1-127
X, P	US 6,541,911 B1 (TANABE et al) 01 April 2003 (01.04.2003), column 10, line 35 to column 11 line 67.	1-127